Stellar occultations by NEAs: high-accuracy astrometry & size determination

Damya Souami, P. Tanga, K. Tsiganis, ACROSS team, & **100+ collaborators**

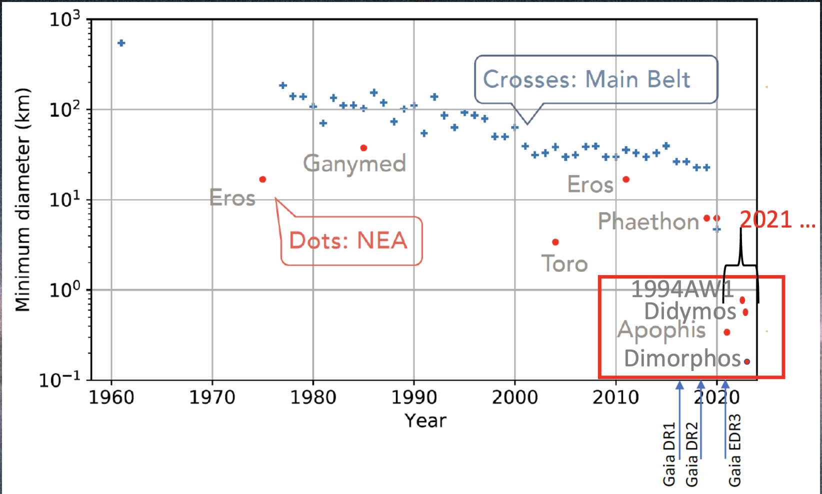
Slides' background, credit: *Gaia* (ESA) mission

First of all ...

Thank you *Gaia*, for direct and indirect discoveries!

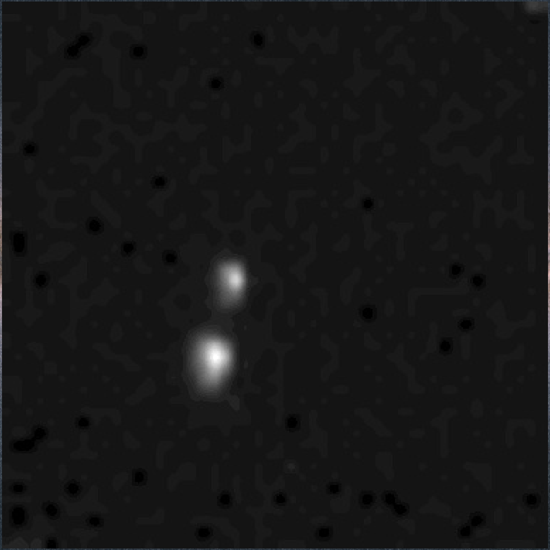
STRUCTURE OF THE TALK

1. Stellar Occultations a powerful method!
2. Occultations by Apophis
3. Occultations by the Didymos-Dimorphos system
4. Lessons learnt !

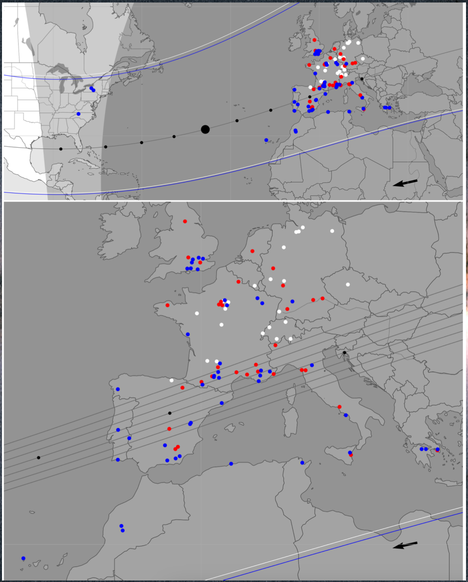


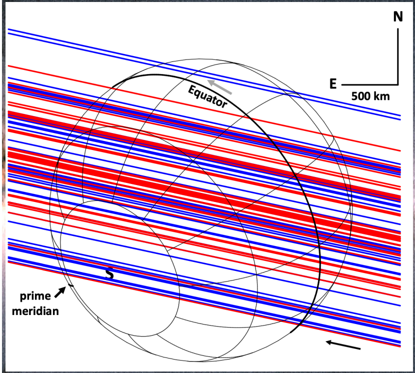
January 1975: 1st occultation by an NEA (Eros)
March 2021: 1st occultation by a sub-km sized object – the NEA Apophis
→ marking the start of a new Era!

STELLAR OCCULTATIONS



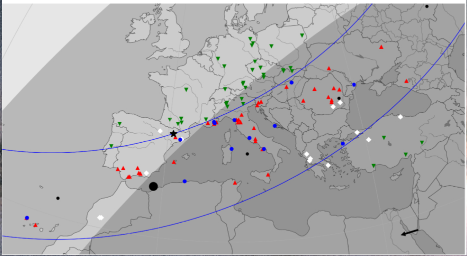
E.g.: Oct. 5th, 2017 Triton occultation

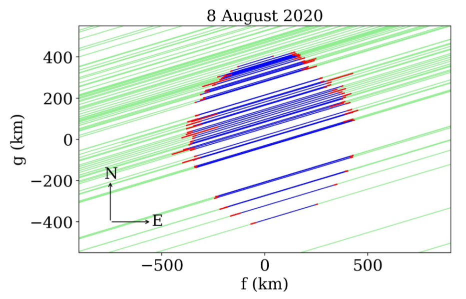




Figures extracted from (Marques Oliveira et al. 2022, A&A)

E.g.: (307261) 2002 MS_4 occultation, on Aug. 8th, 2020





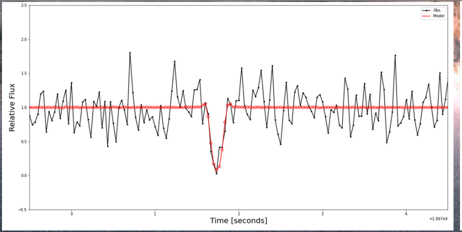
Figures extracted from (Rommel et al. 2023, A&A)

Apophis

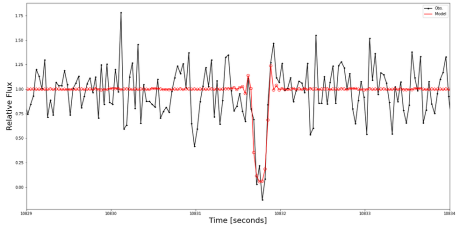
Observations' period	Feb. 22nd, 2021 - Apr. 9th, 2022
Stars' G. mag.	7.0 to 11.0 mag.
Max. expected durations	0.01 s to 0.13 s

10 events: 1 (bad weather), 2 (no detection), 2 inconclusive, 5 successful events!

e.g. light-curves from the 2021-05-06 event. Star 9.0 G mag., during twilight.

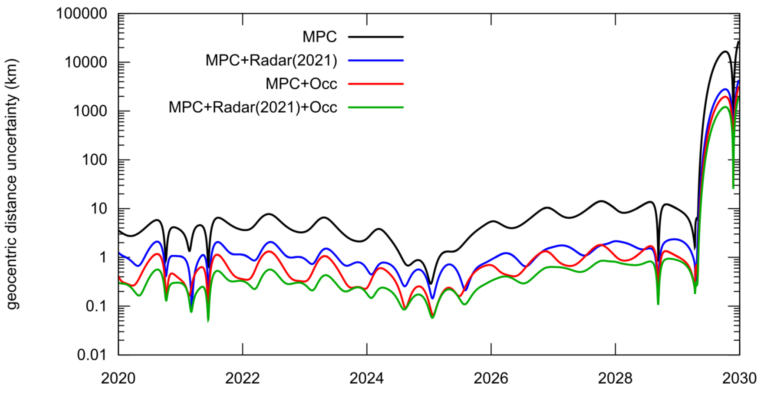


acquisition at 33 Hz,
duration: 0.1837 s,
SNR: 3.058.



acquisition at 33 Hz,
duration: 0.1169 s,
SNR: 6.608.

Evolution (over the years) of our knowledge of the 1σ uncertainty on Apophis' geocentric distance:
using (2004 - 2020) data and the Yarkovsky acceleration $A_2 = (-2.8992 \pm 0.0161) \times 10^{-14}$ AU d^{-2}.

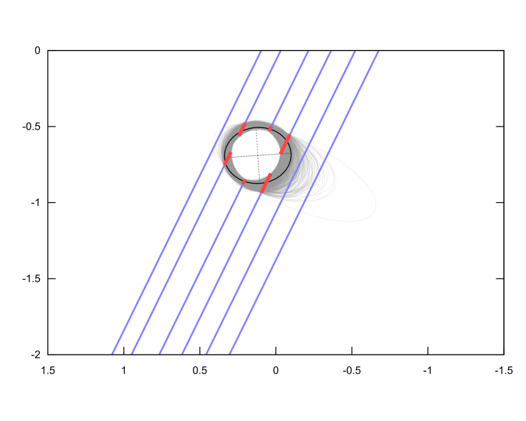


also presented on the poster # 2376, by *Desmars et al.*

Occultation derived astrometry reduces the uncertainty by an order of magnitude.

(paper *in prep.*)

Apophis: size and shape from the



Ellipse fit (km): (0.438 ± 0.057)×(0.368±0.022).

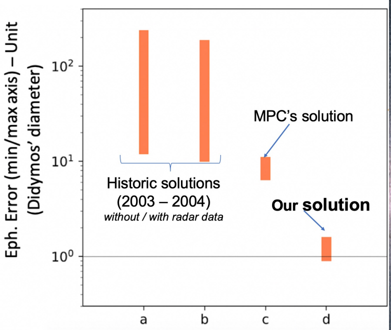
(paper *in prep*)

Didymos-Dimorphos

Preliminary work

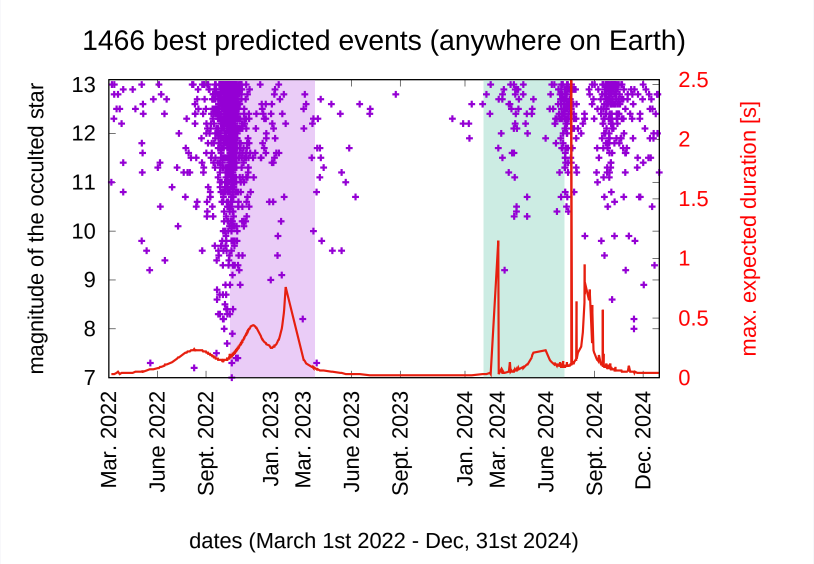
High accuracy astrometry

- applying the GBOT* high-accuracy astrometric pipeline
- Data:
  - DART team (2015 - 2022) data
  - ACROSS (2021 - 2022) data



**Gaia*-GBOT (Ground Based Optical Tracking) was developed for the tracking of the *Gaia* satellite itself, with a 20 mas accuracy (ESAC requirement).

Didymos occultation events



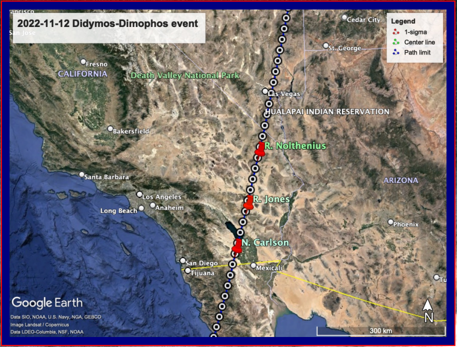
Season 1 - Didymos Occultation campaigns

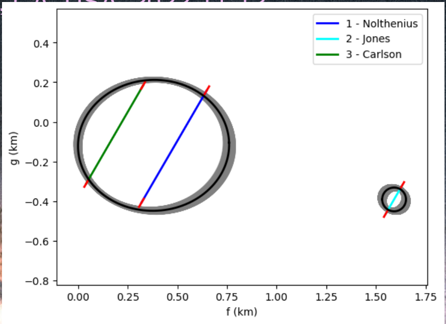
- Before impact

Observations' period	June. 15th, 2022 - Sept. 25th, 2022
Stars' G. mag.	7.0 to 11.0 mag.
Max. expected durations	0.01 s to 0.13 s
Outcome	5 attempts: 3 bad weather, 2 unsuccessful

- After impact:

Observations' period	Oct. 15th, 2022 - Mar. 22nd, 2023
Successful outcomes	20 for Didymos, 4 of which with Dimorphos
Stars' G. mag.	9.0 to 13.5 mag.
Max. expected durations	0.15 s to 0.39 s





Occultation's circumstances:

- Star: 11.51 G. mag.,
- Didymos: 16.3 V. mag.,
- max expected duration 0.3 s,
- expected mag drop 4.8 mag.

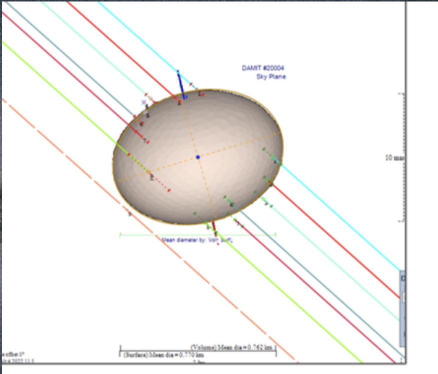
Didymos' preliminary limb fitting at epoch:

→ equatorial radius: (0.38 ± 0.01) km

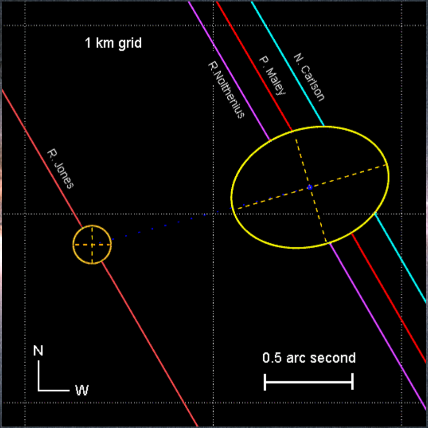
→ oblateness: 0.13

Some prelim. results ...

2022/10/19 – Japan



2022/11/12 – USA

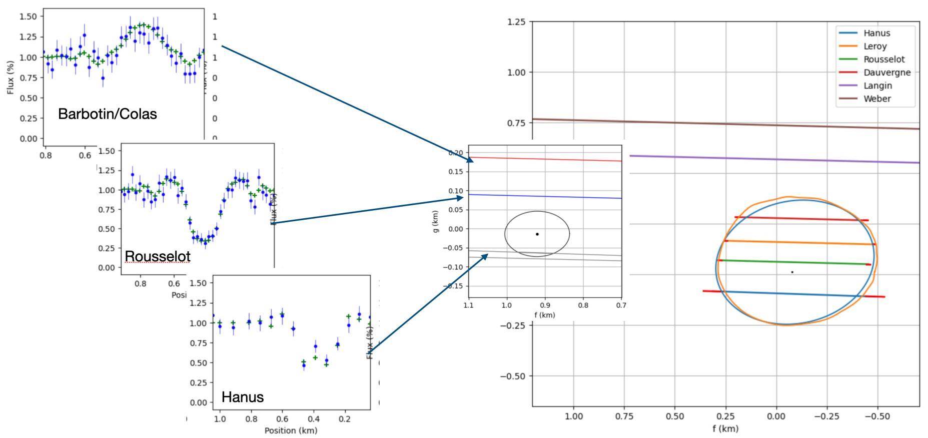


Third detection of both components

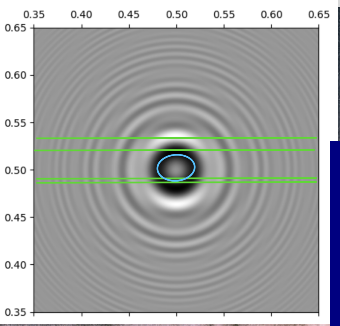
Season 1 – Didymos Occultation circumstances

Epoch (UT)	max. expected duration / mag. ↘	across path 1σ uncer. ($d_{Didymos}$)	Didymos' V. mag. / geocentric Δ (AU)	Stars' G mag.
*2022-10-15	0.15 s / 5.1 mag.	0.441	15.1 / 0.0796	10.34
2022-10-18	0.16 s / 3.0 mag.	0.354	15.3 / 0.0838	12.22
2022-10-18	0.16 s / 4.4 mag.	0.359	15.3 / 0.0849	11.20
*2022-10-19	0.17 s / 3.5 mag.	0.477	15.3 / 0.0859	12.14
2022-10-19	0.17 s / 3.2 mag.	0.478	15.6 / 0.0866	12.43
2022-10-21	0.18 s / 3.6 mag.	0.497	15.7 / 0.0897	11.82
2022-10-26	0.2 s / 4.3 mag.	0.496	15.6 / 0.099	11.32
2022-10-27	0.2 s / 4.0 mag.	0.521	15.7 / 0.1013	11.95
2022-10-27	0.2 s / 4.4 mag.	0.512	16.0 / 0.1021	11.59
2022-11-04	0.25 s / 3.3 mag.	0.073	16.2 / 0.1188	12.90
*2022-11-12	0.3 s / 4.8 mag.	0.104	16.3 / 0.1353	11.51
2022-11-14	0.32 s / 6.2 mag.	0.103	16.3 / 0.1395	10.15
2022-11-15	0.33 s / 4.7 mag.	0.322	16.4 / 0.1415	11.63
2022-12-17	0.29 s / 2.9 mag.	0.211	16.5 / 0.2136	**13.54**
2022-12-19	0.28 s/ 4.7 mag.	0.214	16.4 / 0.2186	11.73
2022-12-23	0.26 s/ 4.5 mag.	0.222	16.4 / 0.2312	11.97
2022-12-29	0.24 s/ 6.0 mag.	0.205	16.4 / 0.2523	10.56
2023-01-18	0.3 s/ 4.12 mag.	0.199	17.2 / 0.3565	13.04
*2023-01-21	0.36 s/ 8.5 mag.	0.206	17.4 / 0.3816	9.07

Highlight on the Jan. 21st, 2022 event



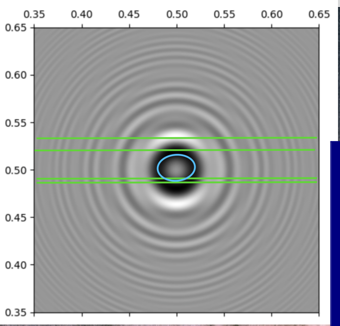
Diffraction by Dimorphos



- The diffraction pattern dominates the occultation photometry when the target's size is ~ fringe separation
- It depends on the occulter shape, size and orientation

→ Very sensitive: position of Dimorphos at ~20 m uncertainty level

Diffraction by Dimorphos



- The diffraction pattern dominates the occultation photometry when the target's size is ~ fringe separation
- It depends on the occulter shape, size and orientation

→ Very sensitive: position of Dimorphos at ~20 m uncertainty level

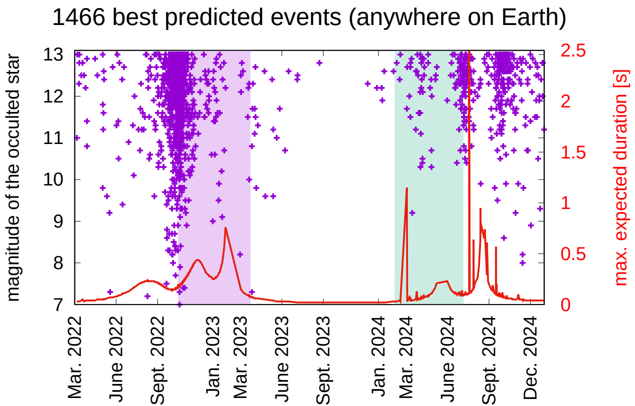
DART post-impact shape

- Determination of semi-major axis, flattening and orientation of the projected shape $\rightarrow a = 0.171^{+0.013}_{-0.011}$; $\varepsilon = 0.711^{+0.103}_{-0.101}$; $P = 90.178^{+13.347}_{-13.361}$

Compatible with (Naidu et al. 2024): $(192 \pm 12) \times (148 \pm 9) \times (117 \pm 15)$ m

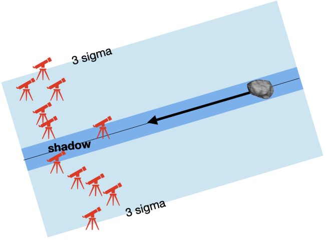
Season 2 - Didymos Occultation campaigns

Observations' period	May 2024 - Sept. 2024
Successful outcomes	3 for Didymos, 1 of which with Dimorphos
Stars' G. mag.	9.9 to 12.4 mag.
Max. expected durations	0.10 s to 0.78 s



How many observers are needed to be sure to catch the target ?

- Optimistic evaluation
  - Ephemeris uncertainty (s) = asteroid size (d)
  - Cross path extension at $3\sigma = 6\,s + d = 7d$
  - Spacing observers $\sim 0.7 \times d$



→ Minimum number of observers = $(7d)/(0.7d)+1 = 11$

- Realistic evaluation
  - technical problems, sky conditions, etc.
  - unknown systematics in the orbital solution ...

TAKEAWAYS ...

- Occultations by sub-km sized NEA are feasible, under optimal conditions.
  → size and positions can be measured down to 50 m accuracy
- Dimorphos (∼150 m is size): smallest objet ever observed by occultation ...
  → and that happened 4 times!
- We clearly show that occultations and radar obs. are complementary.
- Yarkovsky acceleration refined for both Apophis and Didymos.
- ... **The beginning of a new Era!** ... *several papers in prep.*
- **Stay tuned, as the best is yet to come!**

NACHOS 

Successful occultations by NEAs require high-accuracy **Astrometry** and efficient **Communications** , along with **Height** (topography) corrections, to support **Occultation** campaigns & maximise the **Scientific** outcomes.

This work requires organising huge campaigns across the globe! The collaboration with amateurs (citizen astronomers) is crucial in our efforts.

→ requires financial and logistic support for high-value targets!

ACROSS Campaigns

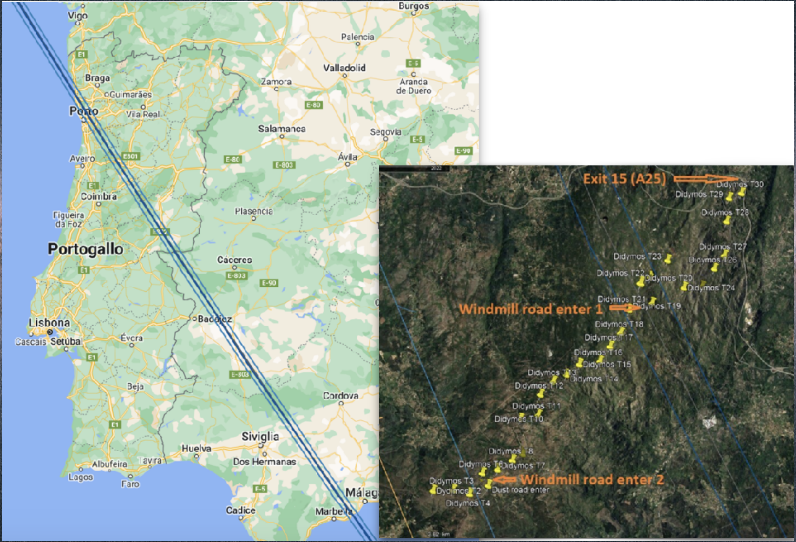
Largest ACROSS (esa funded) campaign – Aug. 25th, 2022

Deployment: Algeria, Spain, Portugal w. 3, 7, & 21 stations, resp.

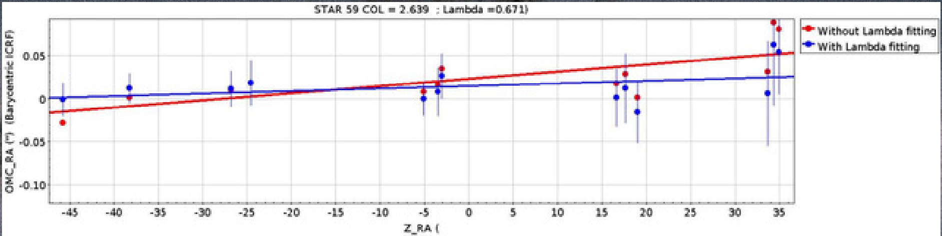
Porto team – North of Porto at *Vila Nova de Gaia*

Largest ACROSS (esa funded) campaign – Aug. 25th, 2022

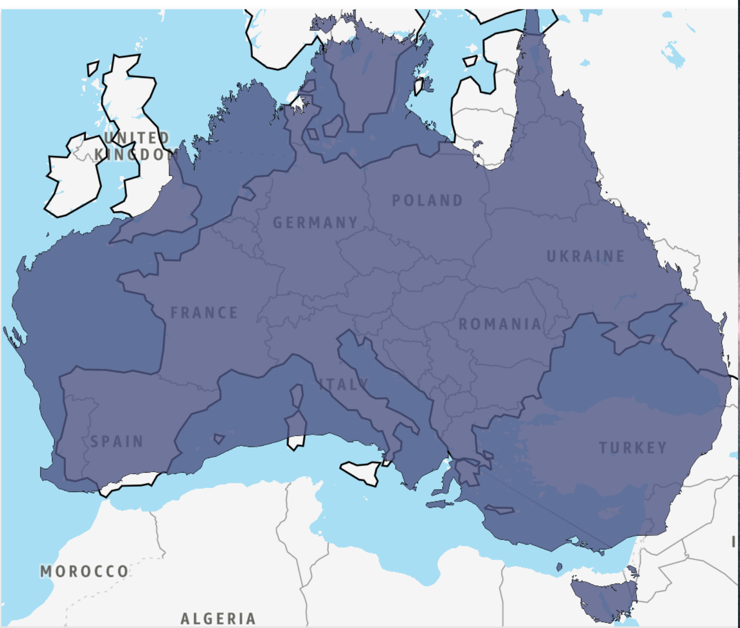
Deployment around Porto



The differential chromatic refraction (DCR) effect



To scale!



UNITED KINGDOM
POLAND
GERMANY
UKRAINE
FRANCE
ROMANIA
ITALY
SPAIN
TURKEY
MOROCCO
ALGERIA